REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
21-08-2009

2. REPORT TYPE
FINAL

3. DATES COVERED *(From - To)*
Mar 2006 - Aug 2009

4. TITLE AND SUBTITLE
A Four-Field Computational Framework for the Aerothermomechanical Analysis of Hypersonic Vehicles

5a. CONTRACT NUMBER
N/A

5b. GRANT NUMBER
FA9550-06-1-0246-P0004

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2016-0670

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified Unlimited

13. SUPPLEMENTARY NOTES
None

14. ABSTRACT
Flight testing hypersonic systems is particularly challenging, because of the speeds at which they operate. When anything unexpected occurs, the time to react is so short that the tested system must be destroyed. Therefore, the predictive analysis of these systems is essential for determining their stability and structural integrity throughout their flight phases. Hypersonic vehicles distinguish themselves from conventional subsonic, transonic, and low-supersonic airframes not only by the complexity of their aerodynamics, but also by their aerothermodynamic input due to a thermal protection system and/or ablation, by all movable control surface motions, and by panel vibrations. For this reason, their predictive analysis hinges on the availability of a high-fidelity aerothermomechanical simulation capability. To this effect, the main objective of this proposal is to develop a four-field computational framework for rigorously integrating the latest advances in computational fluid dynamics, moving grids, structural dynamics and thermomechanics that pertain to hypersonic systems.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
			UU		

Final Report

A Four-Field Computational Framework for the Aero thermomechanical Analysis of Hypersonic Vehicles

Charbel Farhat

FA9550-06-1-0246

For Performance Period:

Mar 2006 - Aug 2009

A Four-Field Computational Framework for the Aerothermomechanical Analysis of Hypersonic Vehicles

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ABSTRACT

Hypersonic systems for space access and with strike capability are currently being researched by the Air Force. Flight testing and clearing them is particularly challenging, because of the speeds at which they operate. When anything unexpected occurs, the time to react is so short that the tested system must be destroyed. Therefore, the predictive analysis of these systems is essential for determining their stability, and their structural integrity throughout their flight phases. Hypersonic vehicles distinguish themselves from conventional subsonic, transonic, and low-supersonic airframes not only by the complexity of their aerodynamics, but also by their aerothermodynamic input due to a thermal protection system and/or ablation, by all movable control surface motions, panel vibrations, and by the complexity of their flight conditions and flight trajectories. For all these reasons, the predictive analysis of hypersonic systems hinges on the availability of a modern, high-fidelity, aerothermomechanical simulation capability. To this effect, the main objective of this proposal is to develop a four-field computational framework for rigorously integrating the latest advances in computational fluid dynamics, moving grids, solid mechanics and structural dynamics, and thermomechanics that pertain to hypersonic systems. The proposed approach centers around a four-field formulation of aerothermoelastic problems, conservative discretization of transmission conditions on non-matching discrete interfaces, discrete conservation laws for constructing and analyzing higher-order unsteady flow solvers on unstructured moving grids, and an original energy-based concept for designing and analyzing computationally efficient algorithms for the solution of coupled large-scale systems of ordinary differential

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fluid/structure/thermal equations on massively parallel processors. The anticipated short-term outcome of this effort is a multidisciplinary analysis framework capable of integrating existing, state-of-the-art, disciplinary analyzers in order to accurately predict the aerothermal loads, the structural temperatures and their gradients, and the structural deformations and stresses associated with hypersonic systems. The anticipated longer-term outcome of this research effort is a significant contribution towards increasing the safety and efficiency of hypersonic flight testing.

1 OBJECTIVES

The objectives of this research proposal are: (a) to develop a four-field computational framework for rigorously integrating the latest advances in computational fluid dynamics, moving grids, solid mechanics and structural dynamics, and thermomechanics that pertain to hypersonic systems, (b) implement this framework in the AERO code deployed at the Flight Test Center and the Edwards Air Force Base, and (c) validate the resulting computational tool with a simple hypersonic problem and demonstrate its potential for more complex ones.

To this effect, the following research goals and corresponding statement of work are formulated.

1.1 RESEARCH GOALS

1) *Four-Field Computational Framework for Aerothermomechanical Analysis.* The three-field formulation of nonlinear computational aeroelasticity introduced a decade ago by the Principal Investigator (PI) models a fluid/structure interaction problem by three coupled partial differential equations: those governing the fluid subsystem written in an Arbitrary Lagrangian Eulerian (ALE) coordinate system, those governing the motion of the fluid mesh, and those governing the dynamic equilibrium of the structural subsystem. The corresponding computational framework is adopted today by a large segment of the computational fluid/structure interaction community. It can address many subsonic, transonic, and low-supersonic aeroelastic problems including flutter, the prediction of steady and unsteady loads and control surface effects in level flight and maneuvering, aeroelastic tailoring, and performance analysis. However, it cannot treat hypersonic problems because it simplifies the treatment of thermal equilibrium to isothermal or adiabatic wall-boundary conditions. Here, the research goal is two-fold: (a) to extend this computational framework to a four-field formulation where heat conduction in the structure is modeled and accounted for, and suitable interface conditions with the surrounding flow are introduced, and (b) to develop and analyze the best corresponding coupling solution methods in terms of accuracy, numerical stability, and computational efficiency.

2) *Integration in AERO and Validation.* AERO is considered by many to be the state-of-the-art of coupled, nonlinear aeroelastic simulation tools. This code is currently used at the Edwards Air Force Base, Lockheed-Martin Aeronautics, the Naval Research Laboratory, the Sandia National Laboratories, and several other institutions for applications ranging from the parametric identification of modern fighters to the design of dynamic data-driven systems for submarine applications. Here, the research goal is also two-fold: (a) to identify a computationally efficient path for transforming the three-field formulation and computational framework implemented in AERO into the four-field formulation and computational framework for hypersonic problems resulting from the previous research goal, and (b) to validate the upgraded AERO simulation platform for a three-inch diameter stainless steel cylinder subjected to Mach 8 shock-shock interference heating.

3) *Technology Demonstration.* To demonstrate its potential for more complex hypersonic systems, the proposed four-field computational framework will be applied to the Generic Hypersonic Vehicle testcase developed by NASA. Here, the research objective is to investigate the aeroelastic effects that may be observed on such a hypersonic vehicle. The anticipated success of this research effort can be expected to pave the way for integrating in AERO and/or other similar multidisciplinary computational environments the state-of-the-art hypersonic flow and reentry aerodynamic heating analyzers that are being pursued elsewhere by the experts in these research areas.

1.2 STATEMENT OF WORK

A four-field formulation of aerothermomechanical problems associated with hypersonic flows will be derived. This formulation will include: (a) a modified version of the Navier-Stokes equations written in an Arbitrary Lagrangian Eulerian (ALE) coordinate system that is suitable for the prediction on moving grids of high-temperature hypersonic flows characterized by $K_n < 0.01$, (where K_n denotes the Knudsen number) (b) a non-linear pseudo-structural system for modeling the motion of the fluid mesh, (c) a diffusion equation for modeling heat conduction in the structure, and (d) a nonlinear form of the structural equations of dynamic equilibrium that accounts for thermal loading and geometrical nonlinearities. These four computational models will be coupled by the appropriate kinematic, temperature, stress, and temperature flux transmission conditions at the fluid/structure interface.

A computational framework associated with this four-field formulation will also be developed and analyzed. This framework will address: (a) the ALE extensions of discretization schemes for the modified Navier-Stokes equations that preserve on moving grids their accuracy and numerical stability properties established on fixed grids, (b) the semi-discretization of the transmission conditions coupling the fluid and structural subproblems by an approach that conserves energy transfer at the fluid/structure interface, (c) the semi-discretization of the transmission conditions coupling the thermofluid and thermostructure subproblems by an approach that is variationally consistent with the semi-discretizations of these two subproblems, and (d) a fast iterative or pseudo-time-stepping implicit algorithm for the solution of coupled fluid/structure/thermal steady-state problems, and (e) a state-of-the-art loosely-coupled time-integrator for time-advancing the solution of all four semi-discretized computational models that is formally second-order time-accurate and characterized by good numerical stability properties.

The computational framework outlined above will be integrated into the AERO code used at the Flight Test Center at the Edwards AirForce Base, and validated with the solution of a Mach 8 shock-shock interference heating problem. Using the Generic Hypersonic Vehicle testcase developed by NASA, the upgraded AERO code will then be applied to the investigation of the aeroelastic effects that may be observed on such hypersonic vehicles, and to demonstrate the potential of the developed multidisciplinary simulation tool.

2 TECHNICAL PROPOSAL

2.1 RESEARCH EFFORT

2.1.1 Introduction

The motivations for building flight vehicles that will travel in the atmosphere at hypersonic speeds have grown during the last two decades [1, 2]. In particular, the Air Force is currently interested in hypersonic systems with a strike capability. Flight testing and clearing these systems is particularly challenging, because of the speeds at which they operate. When anything unexpected occurs, the time to react is so short that the tested system must be destroyed. Furthermore, ground-based experimental facilities such as shock tunnels and arc-jets are typically incapable of reproducing the flight conditions that these vehicles experience during hypersonic travel. For all these reasons, accurate computational models are required for designing these vehicles, and determining their stability and structural integrity throughout their flight phases.

Modeling the physics of hypersonic flow fields is a complex task. These flows are non-ideal, in that they are vibrationally and electronically excited, chemically reacting, and possibly ionizing. Hence, the assumptions of perfect and inviscid gas used in classical aerodynamics do not apply. Boundary layers are typically thick and occupy a large portion of the flow field. They can interact with bow and oblique shocks induced by the geometry of the vehicle. The gas is typically at a high temperature, which causes reactions and thermal excitation. These processes occur at finite rates, which when coupled with the large convection speeds results in a state of thermo-chemical non-equillibrium. The accurate prediction of this non-equillibrium flow is important as it has significant consequences on the pitching moment of the vehicle and the temperature distribution — and hence on heat transfer — on the body [3]. From the numerical view point, hypersonic flows tend to be stiff in that they contain very disparate length and time scales that need to be accurately resolved.

The vibrational and electronic state of the gas and the concentration of highly radiative species have a large influence on the amount of radiation emitted from the shock layer. The degree to which these non-thermal modes are excited determines the importance of radiative heating to the vehicle. Because the surface temperature of a flight vehicle can affect the external flow by changing the amount of energy absorbed by the structure, and the temperature gradients in the structure can induce structural deformations that can alter the flow field, surface pressures, and heating rates, significant coupling can occur between the hypersonic flow field, structural heat transfer, and structural response. For example, tests conducted in the Mach 7 8-ft High-Temperature Tunnel at the NASA LaRC [4] showed that panels bowed-up into the flow to produce heating rates that are up to 1.5 times greater than flat-plate predictions [5]. This and other examples highlight the important role of fluid/structure/thermal coupling in the design and certification of vehicles that are expected to experience severe aerodynamic heating. Therefore, advances in computational methods are needed not only in modeling hypersonic flow fields, but also in the area of modeling and simulation of the coupled aerothermomechanics of hypersonic flight. This was recognized, among others, by the NASA LaRC which initiated more than a decade ago the development of LIFTS, an integrated fluid//structure/thermal analyzer using finite element methods.

The current state-of-the art of coupling fluid, structural, and thermal analyzers for hypersonic vehicles is not significantly different from that of a decade ago [5–7], except perhaps for specific advances in subtopics such as fluid/thermal approaches for ablation (for example, see [8]). Recent efforts appear to have focused on "software integration" more than on "coupled field analysis" — that is, on ensuring that the output of one analyzer can be used as input for another analyzer (for example, see the recent works published in [9, 10]), instead of ensuring that the appropriate transmission conditions are correctly enforced and by the best numerical algorithms. Such approaches are not only low-fidelity, but also computationally inefficient. Changing this paradigm can produce significant payoff. For example in the field of aeroelasticity, the investment in rigorous coupling at both continuous and discrete levels made in AERO [11, 12] is the reason why today, this code is an order of magnitude faster that many counterparts, independently from the speed of the computing platform (for example, see [13]). Operating at such computational efficiency is essential for flight test centers. In this sense, the main objective of this research effort is to advance the state-of-the-art of computational methods for the evaluation of aerothermal loads and the analysis of fluid/structure/thermal interaction phenomena in view of assisting the flight test of hypersonic vehicles.

2.1.2 Research Plan

2.1.2.1 Scope and Approach

The main focus on this research effort is on advancing the state-of-the-art of *coupling* methods for the aerothermomechanics of hypersonic vehicles. Therefore, for simplicity, but without significant loss of generality, two justifiable simplifications are made. It is expected that at some later time, through an interaction with the appropriate experts that could be fostered by AFOSR, these simplifications will be removed by swapping the single discipline analyzers they affect with the state-of-the-art in these areas.

Relatively high Mach number flow simulations over slender bodies have been performed using the Euler equations and were found to give good agreement with experimental data [14]. In [15], the effects of air chemistry on waverider aerodynamics were studied and found to be small for the examples considered therein. Viscous simulations using the Navier-Stokes equations with a turbulence model and perfect gas assumptions [16, 17] have also been used for many high Mach number calculations and were shown to accurately reproduce experimentally measured surface pressure, heating rate, and skin friction. For these reasons, the Navier-Stokes equations equipped with a turbulence model and the perfect gas assumption will be used during the initial phase of the development of the four-field formulation of aerothermomechanics of hypersonic vehicles and its corresponding computational framework. In a second phase, a more accurate model for high temperature hypersonic flows will be constructed by modifying the initial one as follows:

- The conservation of mass equation will be replaced by a species conservation equation for each species in the flow. The latter equation has a form that is similar to that of the continuity equation but contains a source term that predicts the production and/or destruction of each of the species.

- The total momentum equations will be kept unchanged from the perfect gas case except that the molecular viscosity will be that of the mixture.

- The standard energy equation will be augmented with heat conduction terms from the vibrational states of the flow, and an additional energy equation for the vibrational modes will be introduced.

The above modifications lead to a two-temperature model for the fluid which has been shown to work well for many hypersonic flows [24].

Thermal Protection Systems (TPS) are an important constituent of any overall hypersonic reusable vehicle. Accurate models to predict the heat transfer from the high enthalpy flow to the TPS are necessary to prevent failure of this mission critical system, and also to realize the performance objectives of the vehicle along the flight path. TPS can be ablative or non-ablative, depending on the mission requirement. Non-ablative systems are relatively easy to model using well known finite element approximations to the heat conduction equation [18,19]. The effect of heat flux due to convection and radiation is often introduced as boundary conditions to this model, and the temperature field through the structure is often computed by the numerical solution to the heat conduction equation. This model has been made progressively more complex by including radiation and convection terms in the heat conduction equation, and then has been used to study TPS in which there is a significant radiant energy exchange between the different layers in the insulation material [20,21]. Ablative systems provide another level of complexity. The interface between the fluid and the structure moves at the speed of regression, and the additional chemical reactions caused by the burning of the ablative material incur the possibility of energy exchange between the products of ablation and the gases in the boundary layer of the fluid flow. The problem of moving grids to track the ablation surface was studied using an iterative technique in [22], and a model to predict the chemical process of ablation was developed in [23]. For simplicity, but without significant loss of generality for the *coupling* aspect of this research effort, non-ablative systems will be assumed. On the other hand, the effect of heat flux due to convection will not be introduced as a boundary condition but as a transmission condition that couples the heat transfer equation in the structure with the energy equation embedded in the Navier-Stokes model.

Hence, the coupled aerothermomechanical problem will be formulated as a four-field coupled problem as follows:

$$\frac{\partial(Jw)}{\partial t}|_{\xi} + J\nabla_x.(F(w) - \frac{\partial x}{\partial t}w) = J\nabla_x.R(w) \tag{1a}$$

$$\rho_S\frac{\partial^2 u_S}{\partial t^2} - \mathrm{div}(\sigma_S(\epsilon_S(u_S), \frac{\partial \epsilon_S}{\partial t}(u_S), \theta_S)) = b \tag{1b}$$

$$\tilde{\rho}\frac{\partial^2 x}{\partial t^2} - \mathrm{div}(\tilde{\sigma}(\tilde{\epsilon}(x))) = 0 \tag{1c}$$

$$\rho_S c_S\frac{\partial \theta_S}{\partial t} - \mathrm{div}(\kappa_S\nabla\theta_S) - q = 0 \tag{1d}$$

Equation (1a) is the ALE conservative form of the Navier-Stokes equations (equipped with a turbulence model and later with a two-temperature model as outlined above). Here, t denotes the time, $x(t)$ denotes the time-dependent position or displacement of a fluid grid point (depending on the context of the sentence and the equation), ξ its position in a reference configuration, $J = det(dx/d\xi)$, w is the fluid state vector using the conservative variables, and F and R denote respectively the convective and diffusive ALE fluxes. Equation (1b) is the thermoelastodynamic equation where u_S denotes the displacement field of the structure, ρ_S its density, σ_S and ϵ_S denote respectively the stress and strain tensors, θ_S denotes the temperature field in the structure, and b represents the body forces acting on the structure. Equation (1c) governs the dynamics of the fluid grid. It is similar to an elastodynamic equation because the dynamic mesh is viewed here as a pseudo-structural system. A tilde notation is used to designate the fictitious mechanical quantities [25,26]. Equation (1d) is the heat transfer equation that governs the thermal response of the structure, where ρ_S, c_S, and κ_S denote respectively the density, specific heat, and heat conduction coefficient of the structure, and q denotes an internal heat source. For the sake of notational simplicity, the various Dirichlet and Neumann boundary conditions intrinsic to each of the fluid, structure, and heat transfer problems are omitted.

The above mathematical formulation is an extension of the three-field formulation first described in [27] which accounts for thermal effects. structure.

Equation (1a) and Equation (1c) are directly coupled. If u_F denotes the ALE displacement field of the fluid and p its pressure field, σ_F the fluid viscous stress tensor, Γ the fluid/structure interface boundary (wet boundary of the structure), and n the normal at a point to Γ, the fluid and structure equations are coupled by the transmission — or interface boundary — conditions

$$\sigma_S.n = -pn + \sigma_F.n \qquad \text{on } \Gamma \tag{2a}$$

$$\frac{\partial u_S}{\partial t} = \frac{\partial u_F}{\partial t} \qquad \text{on } \Gamma \tag{2b}$$

The first of these two transmission conditions states that the tractions on the wet surface of the structure are in equilibrium with those on the fluid side of Γ. The second of Eqs. (2) expresses the compatibility between the velocity fields of the structure and the fluid at the fluid/structure interface.

The equations governing the structure and dynamic mesh motions are coupled by the continuity conditions

$$x = u_S \qquad \text{on } \Gamma \tag{3a}$$

$$\frac{\partial x}{\partial t} = \frac{\partial u_S}{\partial t} \qquad \text{on } \Gamma \tag{3b}$$

The first of the following additional transmission conditions

$$\kappa_S \nabla \theta_S.n = -\kappa_F \nabla \theta_F.n \qquad \text{on } \Gamma \tag{4a}$$

$$\theta_S = \theta_F \qquad \text{on } \Gamma \tag{4b}$$

describes the conservation of the heat fluxes across the wet surface Γ of the structure. The second of the above two equations expresses the continuity of the temperature field at Γ.

2.1.2.2 Computational Framework for Aerothermomechanical Analysis

It is proposed to investigate the optimal discretization on non-matching meshes of the transmission conditions (4) (that of the transmission conditions (2) is already performed in AERO), and to develop and analyze higher-order energy-transfer-conserving and computationally efficient staggered procedures for the solution on massively parallel processors of the coupled ordinary differential equations resulting from the semi-discretization of the above four-field aerothermomechanical formulation.

Research Issues. Here, the research issues center around the appropriate discretization of the transmission conditions (4), and the computationally efficient solution of the four coupled systems of ordinary differential equations arising from the semi-discretization of the four-field formulation of aerothermomechanical problems.

Approach. The discretization of the transmission conditions (4) will be performed using the conservative framework presented in [28]. The four coupled systems of ordinary differential equations arising from the semi-discretization of the four-field formulation of aerothermomechanical problems will be solved by a state-of-the-art loosely-coupled time-integrator that will be developed for this purpose.

Partitioned procedures and corresponding staggered algorithms [32–34] are often used [35–37] to solve coupled systems of semi-discrete equations such as those arising from the four-field formulation of aerothermomechanical problems outlined above.

In a partitioned procedure for aerothermomechanics computations, the fluid, structure, and thermal subsystems are time-integrated by different schemes that are tailored to their different mathematical models, and solved by a staggered numerical algorithm which is not to be confused with a loosely-coupled solution algorithm. An elementary but popular partitioned procedure for solving aerothermomechanical problems is the Conventional Serial Staggered (CSS) procedure whose generic cycle can be described as follows (see Fig. 1): (1) time-advance the fluid solver, (2) transfer the aerodynamic forces to the structure and the heat fluxes to the thermal subsystem associated with the structure, (3) update the structural temperature under the new heat flux supply, (4) send the new temperature field to the structure, (5) compute the structural displacement under the new fluid and thermal loads, (6) update the fluid mesh. The staggered solution algorithm supporting this partitioned procedure can also be described as a loosely-coupled solution algorithm. However, when equipped with carefully designed inner- or sub-iterations that are performed between each pair of consecutive time-stations [38–40], this staggered algorithm is also often referred to as a strongly-coupled solution algorithm, even though it remains a partitioned solution method.

For any coupled problem, the advantages of partitioning and staggering are numerous. Indeed, this approach reduces the computational complexity per time-step, simplifies explicit/implicit treatment, facilitates subcycling, eases load balancing, achieves software modularity, enables the exploitation of off-the-shelf software components, and makes replacements relatively painless when better mathematical models and methods emerge in the fluid, structure, and thermal subdisciplines. Yet for nonlinear aeroelastic applications, partitioned procedures in general, and loosely-coupled solution algorithms in particular, are often heavily criticized in the literature for their lack of sufficient time-accuracy and sufficient numerical

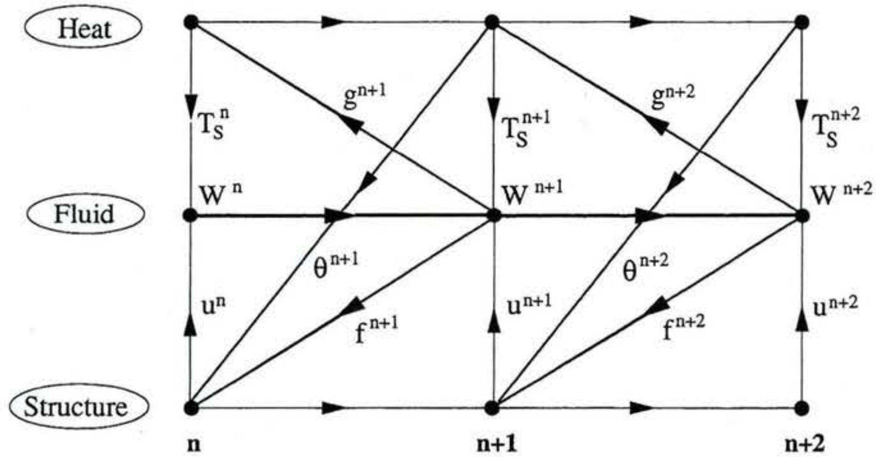

Figure 1: Generic cycle of the CSS procedure.

stability. For this and other reasons, loosely-coupled solution methods are discouraged by both the proponents of monolithic schemes and the advocates of strongly-coupled solution algorithms.

In a monolithic scheme (or what is sometimes referred to in the literature as a fully implicit scheme) for fluid/structure interaction problems, the structure equations of motion are typically assumed to be linear and re-cast in first-order form, then combined with the fluid equations of motion into a single system of first-order semi-discrete equations. Then, this system is solved by a single preferred time-integrator (for example, see [41]). When feasible, such a strategy is usually simpler to analyze mathematically than a partitioned procedure with either a loosely- or strongly-coupled staggered solution algorithm, and delivers in principle the time-accuracy of the chosen time-integrator. For these reasons, it is an appealing solution strategy. This approach — which is the ultimate form of strong coupling — can be extended to fluid/structure/thermal problems. However, it does not acknowledge the differences between the mathematical properties of the fluid, structure, and thermal semi-discrete subsystems. Furthermore, it tends to ignore the issues of software modularity, availability, and integration, even though each of these issues can be in practice a major obstacle. Most importantly, the monolithic approach is memory greedy and can be computationally inefficient. Perhaps for all these reasons, monolithic schemes for nonlinear aeroelastic applications have been demonstrated so far mostly for simple problems.

Whether they are related to accuracy or numerical stability, the observed deficiencies of a loosely-coupled solution algorithm are usually blamed on the "loose" aspect of its coupling mechanism, rather than on one or several of its key components such as the chosen fluid or structure time-integrator, or the algorithm adopted for updating the position of the dynamic fluid-mesh. For this reason, it is often attempted to correct these deficiencies by performing inner- or sub-iterations between each pair of consecutive time-stations. As stated earlier, when equipped with these inner-iterations, the staggered solution algorithm is often referred to as a strongly-coupled solution method. However, inner-iterations increase the complexity of the computer implementation of a coupled fluid/structure/thermal analysis as well as the computational cost of each of its time-steps. Furthermore, it is not clear that a better computational efficiency cannot be obtained simply by reducing the time-step and performing the simulation with a state-of-the-art loosely-coupled version of the chosen staggered solution method. In other words, the computational efficiency of strongly-coupled solution algorithms is debatable except when no loosely-coupled solution algorithm can perform the target fluid/structure/thermal simulation using a reasonable time-step.

It is well-known that the time-accuracy of the CSS procedure is in general at least one order lower than that of its underlying single discipline time-integrators. However, it was shown in [32] for simple linear problems, and in [42] for complex nonlinear ones, that carefully constructed predictors can be introduced to fix this issue. Hence, in this research effort, provably second-order time-accurate, loosely-coupled, and therefore computationally efficient staggered solution procedures will be designed for solving the coupled aerothermomechanics semi-discrete equations using simple mathematical constructs. To this effect, the sources of degradation of time-accuracy for the simplest loosely-coupled solution algorithms will be identified and remedies for them will be designed. These sources go well beyond the loose aspect of the coupling between chosen fluid and structure time-integrators. To this effect, the computational framework developed in [42] for analyzing formally the time-accuracy of loosely coupled fluid/structure time-integrators where the fluid subsystem is solved in moving grids will be extended to address the additional coupling with the heat transfer equation in the structure.

It is also well-known that the numerical stability limit of the CSS procedure can be much more restrictive than that of the flow and/or structure solvers. For this reason, several ad-hoc strategies have been published in the literature for improving the stability properties of the CSS procedure. Most of them consist essentially in inserting some type of predictor/corrector iterations within each cycle of this procedure, in order to compensate for the time-lag between the fluid and structure solvers [38, 39].

In [33], a formal numerical stability analysis of partitioned procedures for the solution of fluid/structure interaction problems was attempted to improve the understanding of their behavior, and design better alternatives to the CSS method. However, because the dependence of the structure equations of equilibrium on the motion of the fluid dynamic mesh is implicit rather than explicit, and the fluid equations of motion can be strongly nonlinear, this analysis was confined to the mathematical investigation of a one-dimensional aeroelastic model problem. This model problem was obtained by linearizing the governing equations around a position of aeroelastic equilibrium. Furthermore, the fluid-mesh motion equation was replaced by transpiration fluxes at the fluid/structure interface, and therefore the model problem was formulated as a two-field and two-way coupled fluid/structure interaction problem. Then, it was proved that an unconditionally stable partitioned procedure, that furthermore retains the order of time-accuracy of its underlying flow and structure time-integrators, can be constructed by superposing a subiteration-free but carefully constructed corrector scheme to the basic CSS method. Based on this mathematical analysis, guidelines were established for exchanging aerodynamic and elastodynamic data in the presence of sub-cycling, in a manner that preserves the unconditional stability and order of time-accuracy of a given partitioned procedure. Unfortunately, it was possible to extend some but not all of these ideas to complex three-dimensional fluid/structure interaction where the fluid is discretized on moving grids.

In [43], an alternative approach for improving the maximum allowable time-step of the CSS procedure that does not increase its computational cost per cycle was described. This approach is based on introducing two computationally economical factors for compensating the time-lag between the fluid and the structure subsystems: (1) a non-trivial prediction of the displacement field, and (2) a non-necessarily trivial transfer of the aerodynamic forces to the structure. More specifically, it was shown in [43] that given two time-integration schemes for the fluid and structure equations of motion, the displacement predictor and transferred force can be designed to achieve a p-order "energy-transfer-accurate" CSS procedure. The higher p is, the closer is the CSS procedure to conserving the transfer of energy through the fluid/structure interface. Using this approach, third-order energy-transfer-accurate loosely coupled procedures were constructed and shown to sustain as large time-steps as those afforded by strongly-coupled or monolithic schemes, without having to pay the usual penalties (see above) associated with these approaches.

Therefore, the stability-oriented design framework presented in [43] will be extended to the case of fluid/structure/thermal problems and combined with the analysis framework of [42] to develop a state-of-the-art loosely coupled staggered procedure for the solution of aerothermomechanics problems that features both second-order time-accuracy and excellent numerical stability properties.

2.1.2.3 Integration in AERO and Validation

AERO is considered by many to be the state-of-the-art of coupled, nonlinear aeroelastic simulation tools. This code is currently used at the Edwards Air Force Base, Lockheed-Martin Aeronautics, the Naval Research Laboratory, the Sandia National Laboratories, and several other institutions for applications ranging from the parametric identification of modern fighters to the design of dynamic data-driven systems for submarine applications. Here, the first research task is to identify a computationally efficient path for transforming the three-field formulation and computational framework implemented in AERO into the four-field formulation and computational framework for hypersonic problems outlined above. The second research task is to validate the upgraded AERO simulation platform. To this effect, the final code will be applied to the study of a three-inch diameter stainless steel cylinder subjected to Mach 8 shock-shock interference heating. References [29, 30] contain pressure and aerothermal load data that can be used to validate the solution prediced by the upgraded AERO for this problem.

2.1.2.4 Technology Demonstration

To demonstrate its potential for more complex hypersonic systems, the proposed four-field computational framework will be applied to the Generic Hypersonic Vehicle testcase developed by NASA [31]. More specifically, the aeroelastic effects that may be observed on such a hypersonic vehicle will be investigated. The anticipated success of this specific task is expected to pave the way for integrating in AERO and/or other similar multidisciplinary computational environments the state-of-the-art hypersonic flow and reentry aerodynamic heating analyzers (i.e. hybrid DSMC-CFD and ablation models) that are being pursued elsewhere by established experts in these technical areas.

2.1.3 Project Schedule, Milestones and Deliverables

The mathematical aspects of the four-field formulation of aerothermomechanical problems and the design of the discretization algorithms for its underlying transmission conditions will be completed during the first year of funding. A preliminary design and implementation in AERO of the corresponding computational framework will be completed and delivered to the Flight Test Center at the Edwards Air Force Base by the end of the second year of funding. The validation using the Mach 8 shock-shock interference heating will be performed during the first quarter of the third year of funding. The investigation of the aeroelastic effects that may be observed on a generic hypersonic vehicle will be performed during the remainder of the third year of funding.

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2.2 PRINCIPAL INVESTIGATOR TIME

2.2.1 Time Committment to this Research Project

The PI of this proposed research project is Professor Charbel Farhat. He will dedicate at least 5% of his academic time to the proposed research effort. Professor Farhat will also supervise one part-time post-doctoral assistant who will contribute to the proposed research project.

2.2.2 Current and Pending Support

Professor Farhat is currently the PI of the following research grants which extend beyond March 1st, 2006:

- Grant: Acoustic Signatures of Mines Located Near the Ocean Bottom. Agency: High Performance Technologies Inc. Commitment: 5% AY.
- Grant: A Dynamic Data-Driven System for Structural Health Monitoring and Critical Event Prediction. Agency: National Science Foundation. Commitment: 5% AY and 0.5 month summer.
- Grant: Aerodynamic/Aeroelastic Effects on a Class of High-Speed Vehicles. Agency: Toyota Motor Corporation. Commitment: 5% AY.
- Grant: High-Resolution Methods for the Solution of Direct and Inverse Acoustic Scattering Problems. Agency: Office of Naval Research. Commitment: 10% AY and 0.5 month summer.
- Grant: A Collaborative for Naval Computational Mechanics. Agency: Office of Naval Research. Commitment: 10% AY and 0.5 month summer.
- Grant: High Performance Computing Modernization Program – Programming Environment and Training (PET). Agency: High Performance Technologies Inc. Commitment: 5% AY.

- Grant: Scalable Substructuring Methods for Linear and Nonlinear Dynamics Problems. Agency: Sandia National Laboratories. Commitment: 10% AY and 0.5 month summer.
- Grant: Hybrid Unsteady Simulation for Helicopters. Agency: Defense Advanced Research Projects Agency. Commitment: 5% AY and 1 week summer.

2.3 FACILITIES

Professor Farhat operates at Stanford University a High-Performance Computing and Visualization Laboratory that can serve as a development and application platform for the proposed research. The laboratory is equipped with a Linux Cluster system with 160 Intel Xeon 3.056 GHz processors and 320 GBytes of memory. This parallel processor is connected to a Panasas Storage Cluster with direct node-to-disk access and to several front-end and visualization systems.

2.4 KEY PERSONNEL

The key personnel for this proposed research project includes Professor Charbel Farhat and a post-doctoral research assistant.

2.4.1 Charbel Farhat

Biographical Sketch

Charbel Farhat is Professor of Mechanical Engineering, Professor, by courtesy, of Aeronautics and Astronautics, and Professor in the Institute for Computational and Mathematical Engineering, all at Stanford University. Previously, he held the positions of Professor and Chair of Aerospace Engineering Sciences and Director of the Center for Aerospace Structures at the University of Colorado at Boulder. He holds a Ph.D. in Civil Engineering from the University of California at Berkeley (1987). He is the recipient of several prestigious awards including the Institute of Electrical and Electronics Engineers (IEEE) Computer Society Gordon Bell Award (2002), the International Association of Computational Mechanics (IACM) Computational Mechanics Award (2002), the Department of Defense Modeling and Simulation Award (2001), the US Association of Computational Mechanics (USACM) Medal of Computational and Applied Sciences (2001), the IACM Award in Computational Mechanics for Young Investigators (1998), the USACM R. H. Gallagher Special Achievement Award for Young Investigators (1997), the IEEE Computer Society Sidney Fernbach Award (1997), the American Society of Mechanical Engineers (ASME) Aerospace Structures and Materials Award (1994), and the United States Presidential Young Investigator Award (1989).

Professor Farhat is currently Vice Chair of the Society for Industrial and Applied Mathematics' Activity Group on Supercomputing (2003-2006), and Associate Editor of the International Journal for Numerical Methods in Engineering. He also serves on the editorial board of eleven other international scientific journals, and on the technical assessment board of several national research councils and foundations. He is a Fellow of the American Society of Mechanical Engineers (2003), Fellow of the International Association of Computational Mechanics (2002), Fellow of the World Innovation Foundation (2001), Fellow of the US Association of Computational Mechanics (2001), and Fellow of the American Institute of Aeronautics and Astronautics (1999). He has been an AGARD lecturer on aeroelasticity and computational mechanics at several distinguished European institutions, and a keynote speaker at numerous international scientific meetings. He is the author of over 200 refereed publications on fluid/structure interaction, computational fluid dynamics on moving grids, computational structural mechanics, computational acoustics, supercomputing, and parallel processing. His research program has been and is currently funded by several government and private agencies including the National Science Foundation, the Air Force Office of Scientific Research, the NASA Langley Research Center, the NASA Ames Research Center, the NASA Lewis Research Center, the Naval Research Laboratory, the Office of Naval Research, the Department of Energy, the Sandia National Laboratories, the Defense Advanced Research Projects Agency, TRW, the FMC Corporation, the Lockheed-Martin Corporation, High Performance Technologies, and the Toyota Motor Corporation.

Selected Publications

1 C. Farhat, G. van der Zee and P. Geuzaine, "Provably Second-Order Time-Accurate Loosely-Coupled Solution Algorithms for Transient Nonlinear Computational Aeroelasticity," *Computer Methods in Applied Mechanics and Engineering, (in press)*

2 C. Farhat, B. Argrow, M. Nikbay and K. Maute, "Shape Optimization with F-Function Balancing for Reducing the Sonic Boom Initial Shock Pressure Rise", *The International Journal of Aeroacoustics*, Vol. 3, pp. 361-377 (2004)

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4 B. Koobus and C. Farhat, "A Variational Multiscale Method for the Large Eddy Simulation of Compressible Turbulent Flows on Unstructured Meshes – Application to Vortex Shedding," *Computer Methods in Applied Mechanics and Engineering*, Vol. 193, pp. 1367-1384 (2004)

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6 P. Geuzaine, G. Brown, C. Harris and C. Farhat, "Aeroelastic Dynamic Analysis of a Full F-16 Configuration for Various Flight Conditions," *AIAA Journal*, Vol. 41, pp. 363-371 (2003)

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8 M. Lesoinne and C. Farhat, "A CFD Based Method for Solving Aeroelastic Eigenproblems in the Subsonic, Transonic, and Supersonic Regimes," *AIAA Journal of Aircraft*, Vol. 38, pp. 628-635 (2001)

9 S. Piperno and C. Farhat, "Partitioned Procedures for the Transient Solution of Coupled Aeroelastic Problems - Part II: Energy Transfer Analysis and Three-Dimensional Applications," *Computer Methods in Applied Mechanics and Engineering*, Vol. 190, pp. 3147-3170 (2001)

10 C. Farhat, M. Lesoinne, P. LeTallec, K. Pierson and D. Rixen, "FETI-DP: A Dual-Primal Unified FETI Method - Part I: A Faster Alternative to the Two-Level FETI Method," *International Journal for Numerical Methods in Engineering*, Vol. 50, pp. 1523-1544 (2001)

2.5 COST PROPOSAL

The budget includes yearly support for: 27% of the time of one post-doctoral research assistant with expertise in coupled field problems; 5% of the academic time of the PI to supervise and contribute to this research project; and travel to attend a technical conference pertaining to the proposed research effort.